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Cyclic plasticity of structural elements made of materials which exhibit the yield-point phenomenon

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Abstract

At first transition from the elastic into the elasto-plastic region, many materials which structural elements are made from exhibit the yield-point phenomenon. In the event of uniaxial cyclic experiments, the yield-point phenomenon is visible only in the first cycle. However, the authors of this paper have proven that the yield-point phenomenon affects the stress-strain response during the entire lifetime of structural elements which are subject to cyclic plasticity. Taking account of the yield-point phenomenon in constitutive models of cyclic plasticity significantly improves the forecast of the stress-strain response and the lifetime of structural elements. For constitutive models of cyclic plasticity, a description and benefit of the yield-point phenomenon during the development of the stress-strain state of a cyclically loaded structural element are presented by comparing experiment and numerical simulation results. In the paper, the emphasis is placed on detailed determination of the benefit as well as the functionality and necessity of taking account of the yield-point phenomenon in constitutive models of cyclic plasticity.

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1. Introduction

At first transition from the elastic into the elasto-plastic region, annealed low-alloy steels as well as aluminium and titanium alloys exhibit a typical sharp yield point and an immediate stress drop followed by a stress plateau (also known as the Lüders plateau) and further hardening (Fig 1). The phenomenon,

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also known as the yield-point phenomenon, is not taken account of by most existing constitutive models of cyclic plasticity [1, 2]. In the event of cyclic loading of structural elements, the plastic-strain region is usually covered by the elastic-strain region [3]. In the event of not taking account of the yield-point phenomenon during numerical simulations of cyclic plasticity, major derogations occur in the forecast of the size and location of the plastic strain region as well as in the forecast of the plastic strain course during cyclic plasticity and the size of the accumulated plastic strain. Precise stress-strain analyses require a model which accurately describes the yield-point phenomenon as well as the subsequent cyclic plasticity.

In the past, authors presented the equations of the yield-point phenomenon [3, 4] and successfully combined them with other equations of cyclic plasticity. To enable a better understanding of the influence of the yield-point phenomenon on cyclic plasticity of structural elements, in the first part of the paper the functioning of the model is presented. In the second part, the benefit of the model on cyclic plasticity of a console beam is presented. A comparison of experiment and numerical simulation results for the event of taking and not taking account of the yield-point phenomenon shows a significant benefit of the description of the yield-point phenomenon in constitutive models of cyclic plasticity.

2. Cyclic plasticity and yield-point phenomenon

Cyclic plasticity is a process in which a material is subject to a sequence of periodic or random elasto-plastic strains. Despite the awareness of the changes in the material on the micro scale, the widely applicable constitutive models for the description of the cyclic elasto-plastic strain-stress response are developed in accordance with the phenomenological approach. The equations of the phenomenological approach are based on prepositions and findings obtained through material observation on the macro scale, and not based on the changes of the micromechanical state of the material.

Equations proposed by the phenomenological approach describe yielding and changing of the size and the position of the elastic region within the stress space. Isotropic cyclic hardening or softening describes the phenomenon in which the yield surface changes in all directions of the stress space equally by increasing the number of cycles. The description of non-linear kinematic hardening describes the displacement of the elastic region within the stress space also known as the Bauschinger effect. The yield surface is described by the yield law; often the von Misses law is applied [3].

Authors presented a unique method of describing the yield-point phenomenon [ref], which is based on the phenomenological approach. The yield-point phenomenon exhibits two interesting phenomena. The first one is evident from the stress-strain curve in the event of monotonous loading. At the transition of the yield limit, a stress drop is evident which is followed by a stress plateau and further material hardening. This phenomenon is evident from the results of the tension and compression monotonous experiment. Therefore, a conclusion can be made that the stress drop is an isotropic process. A significant phenomenon connected to the yield-point phenomenon is also a change in the size of the elastic region within the stress space during the development of the Lüders strain. The experiment results show that at first transition of the yield point the elastic region within the stress space quickly begins to decrease in size and continues to do so until the transition from the stress plateau into the hardening region. The formulation of equations for the description of the yield-point phenomenon should enable realization of the following condition: within the stress plateau region, the model must enable constant velocity as well as track the yield stress change and the displacement of the elastic region centre. Consequently, we propose a description which takes account of both the change in the size of the elastic region within the stress space and the displacement of the elastic region centre (Fig. 1). The displacement of the elastic region centre is determined by kinematic hardening. The appropriateness of our proposal is also

confirmed by the experiment results (Fig. 1). In accordance with the experiment results, two types of yield stress were implemented:

- The yield stress at first transition. This type of stress applies to materials which have not yet been subject the plastic strain. This type of yield stress is marked as σ_{Ypre} .
- The yield stress after the formation of the inhomogeneous plastic strain (Lüders strain) in the material. This type of stress is usually lower than yield stress when the material has not yet been subject to the plastic strain. A stress decrease is resulted from the release of loosely pinned dislocations. This type of yield stress is marked as σ_{Ypost} .

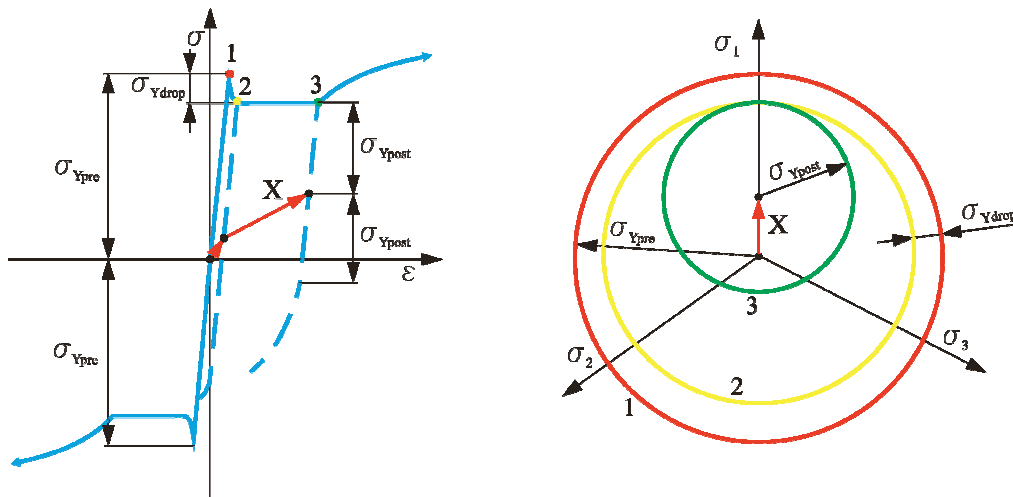


Fig. 1: Change in the elastic region size and position – concept of the constitutive model [3]

The proposed model [3] is in accordance with the experiment findings. Within the stress plateau region, it continuously decreases the size of the elastic region and changes the position of the elastic region centre by increasing the plastic strain so that the stress within the Lüders strain region remains constant. The presented equations of the yield-point phenomenon are based on the effective value of the displacement of the elastic region centre which is determined by the equations of kinematic hardening. The description of the yield-point phenomenon is therefore compatible with numerous models of kinematic hardening which are based on the so-called »back stress« method. The equations of the yield-point phenomenon are rather simple, which enables simple implementation into the existing constitutive models, simple calculations and simple determination of material parameters. Simple determination of material parameters and compatibility between the equations of the yield-point phenomenon and numerous equations of kinematic hardening make the model widely applicable. All parameters necessary for the description of the yield-point phenomenon can be determined based on the existing experiments necessary for the determination of kinematic and isotropic hardening parameters.

3. Benefits of taking into account the yield point phenomenon in constitutive models of cyclic plasticity

The presented manner of describing the yield-point phenomenon in constitutive models of cyclic plasticity is based on the findings obtained from uniaxial tension-compression monotonous and cyclic experiments. The constitutive model proposed by authors [3] enable determination of the multiaxial

stress-strain state which furthermore proves the reasonableness of model verification performed on a structure which is subject to multiaxial stress-strain state. It is our estimate that a comparison between the results of experimental observation and the results of numerical simulations of console beam cyclic plasticity is an appropriate verification method. During cyclic plasticity of a console beam, two local regions of plastic strain occur which are covered by the elastic strain region. Therefore, based on a comparison between experiment and numerical simulation results, the benefit of the proposed manner of describing the yield-point phenomenon can be presented. Experimental tests and numerical simulations of the cyclic loading of a console beam were carried out by means of a displacement control technique with an amplitude of 2 mm.

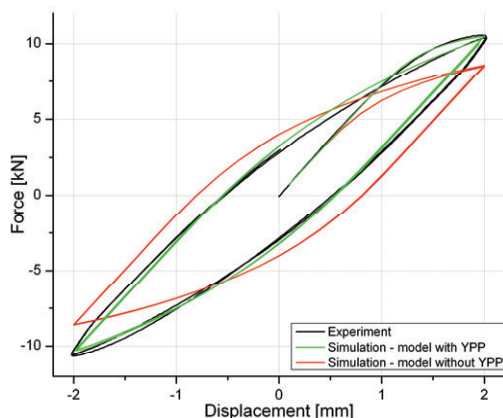


Figure 2: Comparison of hysteresis loops force-displacement for the first and second cycle during symmetrical loading at a displacement amplitude equal to 2 mm

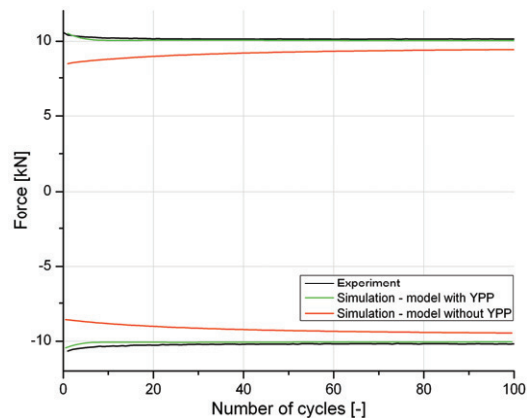


Figure 3: Comparison of force amplitudes during cyclic loading at a symmetrical displacement amplitude equal to 2 mm

The paper presents a comparison of hysteresis loops force-displacement for the first and second cycle as well as the flow of force or displacement amplitudes in relation to the number of cycles. Figure 3 presents hysteresis loops force-displacement for the first and second cycle which are obtained through experimental observation and numerical simulations. The comparison shows a very good agreement between experiment and simulation results in the event of taking account of the yield-point phenomenon, whereas the simulation results deviate in the event of not taking account of the yield-point phenomenon. The same agreement or disagreement between simulation and experiment results is shown in the comparison of force amplitudes in relation to the number of cycles (Fig. 4).

The accumulated plastic strain is also significant for the forecast of the lifetime of cyclically loaded machine parts which is enabled through constitutive models. Fig. 4 shows a comparison of the accumulated plastic strain after the first 100 cycles in the event of both taking and not taking account of the yield-point phenomenon. The figure indicates that in the event of taking account of the yield-point phenomenon the region is smaller, while the size of the maximum plastic strain is bigger by approximately 15 %. It can also be observed that in the event of taking account of the yield-point phenomenon the plastic strain accumulates more locally.

Also presented is a comparison of total strains. During experimental observation of strain regions, we were limited by the size of the observed surface which can be monitored by means of the optical measurement system. Therefore, the results of numerical simulations apply to the same surface, which enables a better overview and comparison of results. Strain comparisons apply to the first and hundredth cycle. A comparison of maximum strains of a console beam in the first and hundredth cycle is shown in

Figure 5. It is evident from the figure that in the event of taking account of the yield-point phenomenon the region of strains equal to or bigger than 0.3 % extends deeper towards the neutral axis of a console beam and within a shorter region than in the event of not taking account of the yield-point phenomenon. The difference is even more obvious in the first cycle where it is evident that in the event of taking account of the yield-point phenomenon the shape of the strain flow is more similar to experiment results than in the event of not taking account of the yield-point phenomenon.



Fig. 4: Accumulated plastic strain after the first 100 cycles during symmetrical cyclic loading at a displacement amplitude equal to 2 mm in the event of taking (above) and not taking (below) account of the yield-point phenomenon

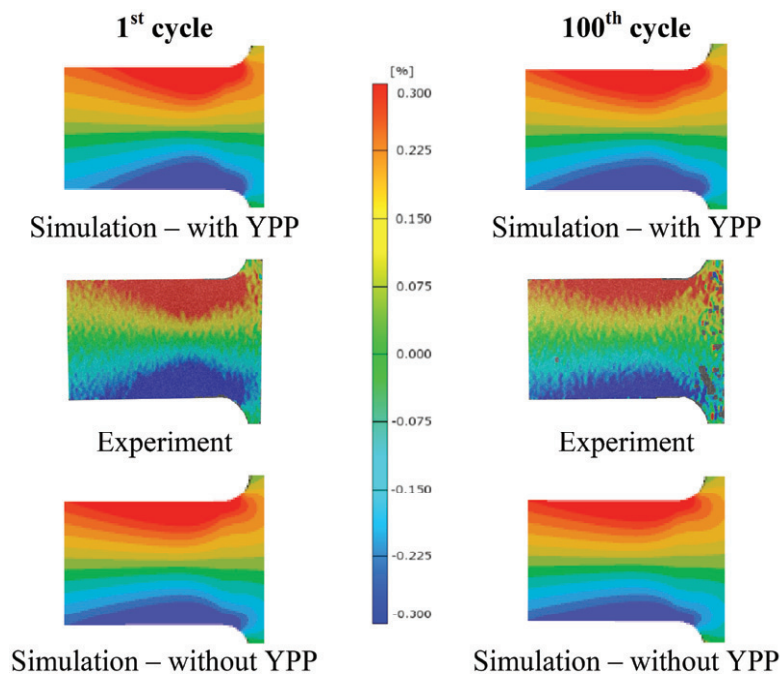


Fig. 5: Comparison of maximum strains of a console beam at displacement amplitude equal to 2 mm

4. Conclusion

The connection between the description of the yield-point phenomenon and the effective value of the displacement of the elastic region centre within the stress space was described. Significant change in the elastic region in the stress space and connection with the displacement of the elastic region in the stress space is the most important part of the yield point phenomenon. Author shows, that this phenomenon has a significant influence on the response of structural elements subjected to cyclic plasticity.

In order to verify the proposed model in the event of multiaxial stress-strain state and for the purpose of presenting the benefit of determining the yield-point phenomenon in constitutive models of cyclic plasticity, cyclic plasticity of a console beam is presented. Based on the presented results of cyclic plasticity of a console beam, it is evident that the benefit of taking account of the yield-point phenomenon is much bigger than can be observed in the event of uniaxial simulations. In the event of uniaxial loading, the benefit is evident only at first transition from the elastic into the elasto-plastic region and is reflected in the shape of the yield plateau and a significant decrease of yield stress [3]. During the observation of the cyclic plasticity of a console beam, the essence of the benefit is revealed. The benefit is not visible only in the first cycle, but rather during the entire cyclic plasticity process. Taking account of the yield-point phenomenon is also significant for the forecast of the stress-strain response of cyclically loaded items which are subject to the local plastic strain.

Verification and presentation of the benefit of taking into account the yield-point phenomenon in constitutive models of cyclic plasticity confirm not only the appropriateness of the proposed model but also the need for its application. Therefore, determination of the yield-point phenomenon presents a major benefit in the field of cyclic plasticity of the materials which exhibit the yield-point phenomenon.

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